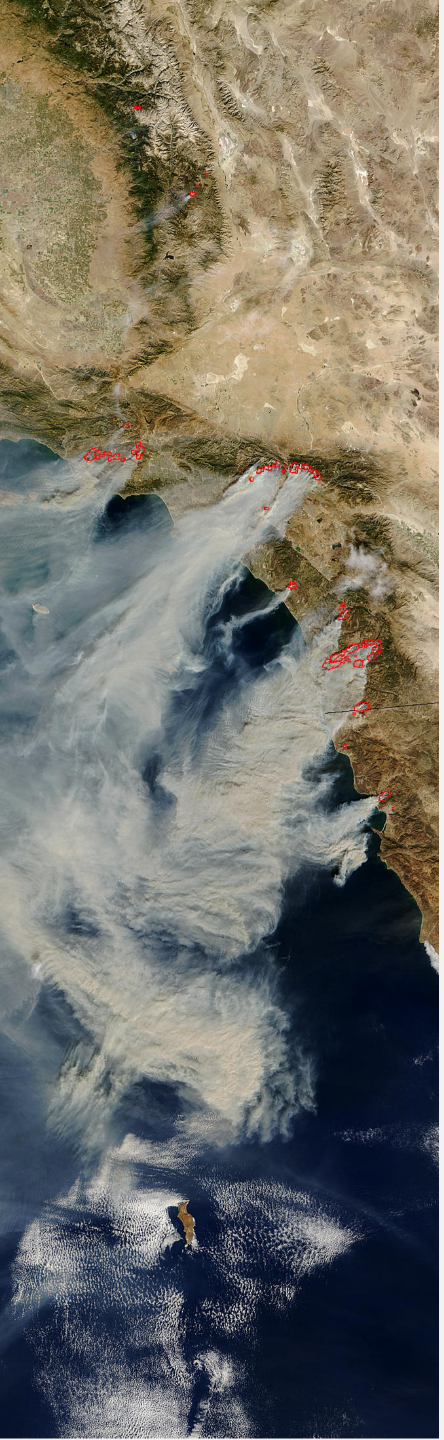


National Aeronautics and
Space Administration

ARSET

Applied Remote Sensing Training
http://arset.gsfc.nasa.gov
@NASAARSET

Estimation of Emissions From Satellites: Trace Gases

Melanie Follette-Cook, Pawan Gupta

Satellite Remote Sensing of Air Quality

Tuesday, Sep 19, 2017 – Thursday, Sep 21, 2017
University of California, Riverside

Learning Objectives

By the end of this presentation you will be able to:

- List several ways satellite observations of trace gases can be used to estimate surface emissions or supplement current emissions inventories
- Learn about relevant data products and satellite retrievals that have near-surface sensitivity

Satellite Remote Sensing of Trace Gases for Air Quality

Overview

- With advances in the detection of atmospheric pollution from space, atmospheric composition can be measured at higher spatial and temporal resolutions
- If chemistry and transport can be accounted for, satellite observations can be used to estimate emission rates

Review articles:
Streets et al. 2013, Atmospheric Environment
[Emissions estimation from satellite retrievals: A review of current capability]
Duncan et al. 2014, Atmospheric Environment (free)
[Satellite data of atmospheric pollution for U.S. air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid]

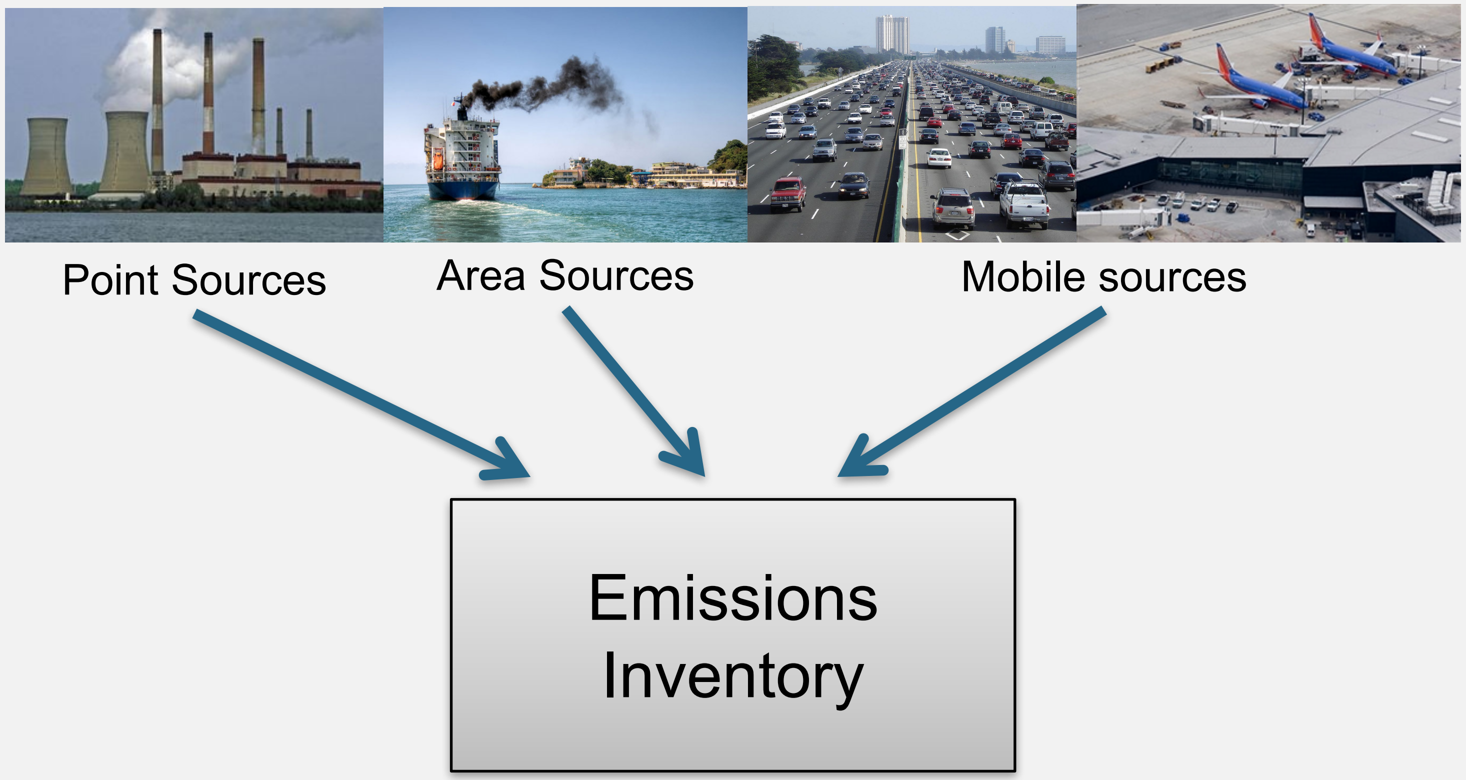
Satellite Remote Sensing of Trace Gases for Air Quality

Types of emissions that satellite observations can help constrain

- Anthropogenic point source emissions
  - Power plants
- Natural point sources
  - Volcanoes
- Anthropogenic area sources
  - Energy extraction, shipping emissions, megacities
- Natural area sources
  - Biomass burning, soils, lightning, biogenic

Bottom-Up Emissions Inventories

- Big undertaking
- Dependent on historical information
- Dependent on sparse spatial and temporal network



Power plant image: http://cbf.typepad.com/
Ship image: http://www.un.org/
Cars image: By User Minesweeper on en.wikipedia
Airplane: http://www.gettyimages.com/

Methods

Methods

- Inverse Modeling
- Oversampling
- Temporal updates to trends or variability

Inverse Modeling

- Attribute changes in observed concentrations to changes in emissions
- Constrains emissions using:
  - Observations (e.g. satellite measurements)
  - Background information (a priori)
  - Model simulation of the observed quantity with associated error estimates[1]

[1]Streets et al. (2013) Atmos. Environ.

Inverse Modeling – Mass Balance

Basic Mass Balance Method

$$E_s = \alpha * \Omega_{observed}$$

Observed atmospheric column

Emission of species, s

$$\alpha = \left(\frac{E_a}{\Omega_m}\right)$$

A priori emissions inventory

Model atmospheric column

Inverse Modeling

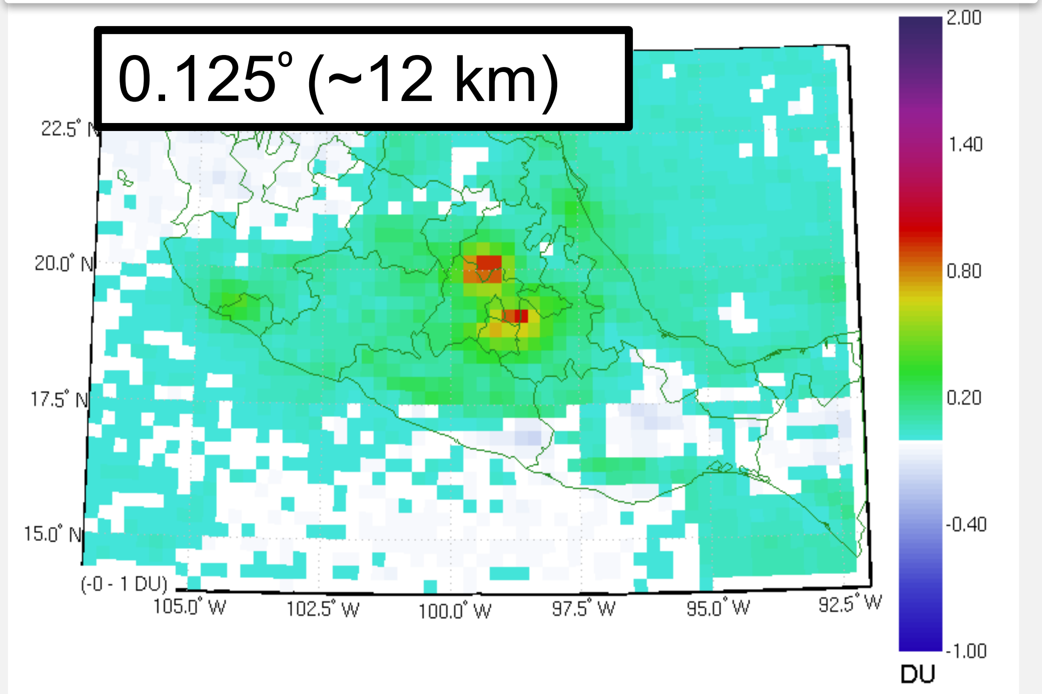
- Becomes more complicated and computationally expensive as the number of observations increases

- Often uses Bayes theory, which is used to describe the probability of an event, given prior knowledge of other probabilities
- Most inversion methods seek to minimize a cost function or equivalently, use the pdf of the predicted values to find the value that represents the most likely choice (i.e. the maximum of the pdf)

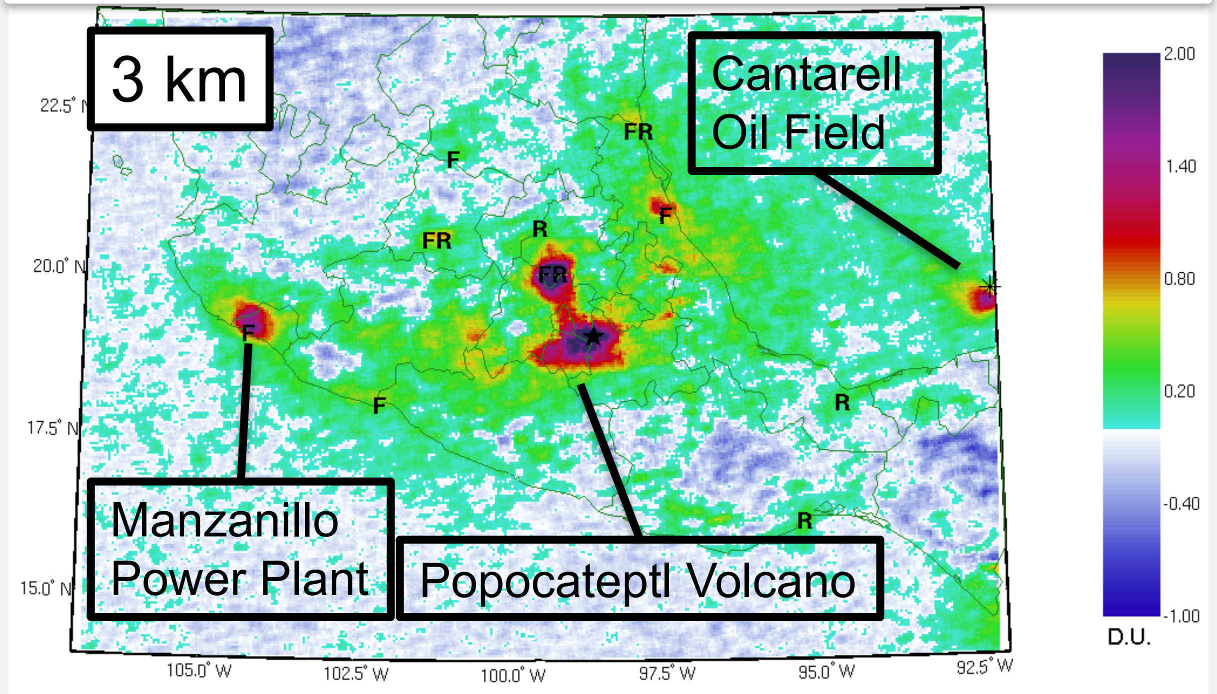
Oversampling

- By averaging at high resolutions over longer time intervals, it is possible to increase the resolution of the original data

OMI SO_2 Over Mexico, 2004-2007



Oversampled OMI SO_2 Over Mexico



Ben de Foy: https://dnr.mo.gov/env/apcp/docs/emissioninventories.pdf

F: Fuel Oil Power Plant R : Refinery

Temporal Variations

Updating Inventory Trends

- Creating a bottom up emissions inventory is time consuming and labor intensive
  - e.g., Currently the most up-to-date U.S. emissions inventory is the NEI 2014
- Satellite observations and trends can be used to update bottom-up emissions inventories until a new inventory is completed
- Example: Lamsal et al. 2011 used a chemistry transport model to estimate how changes in emissions related to changes in the atmospheric column
- Then they applied this relationship using post-inventory satellite observations

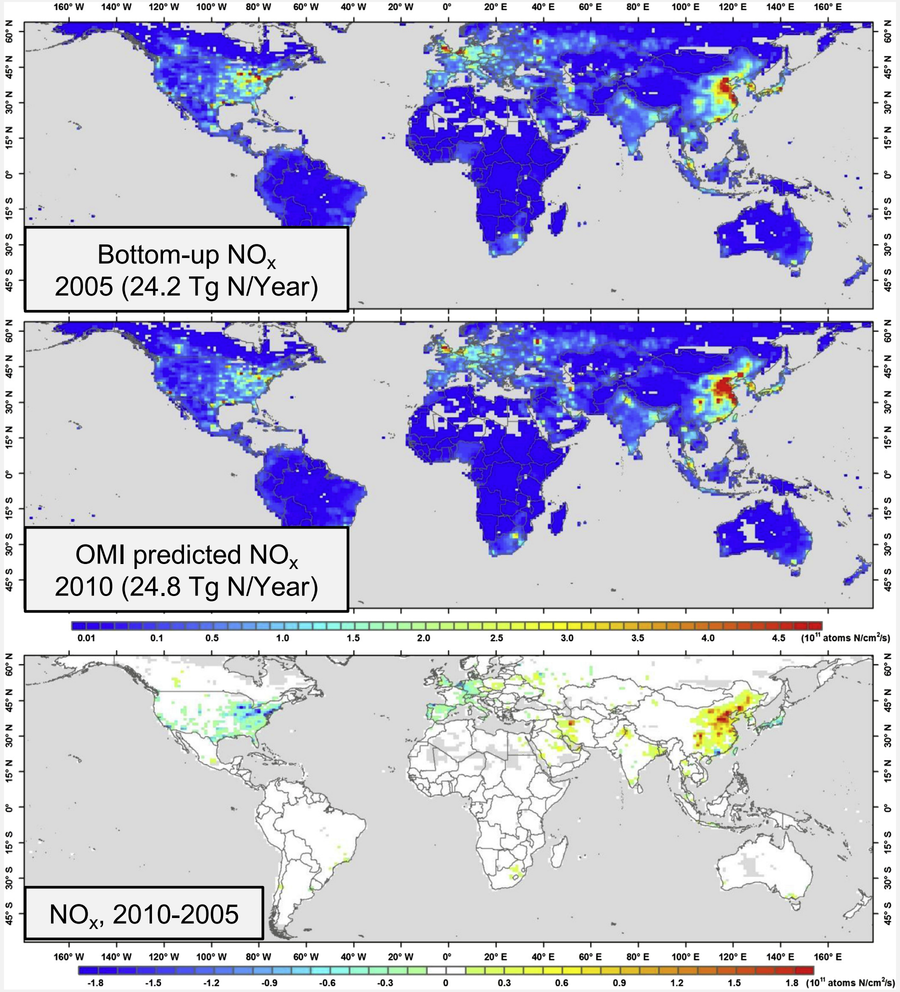
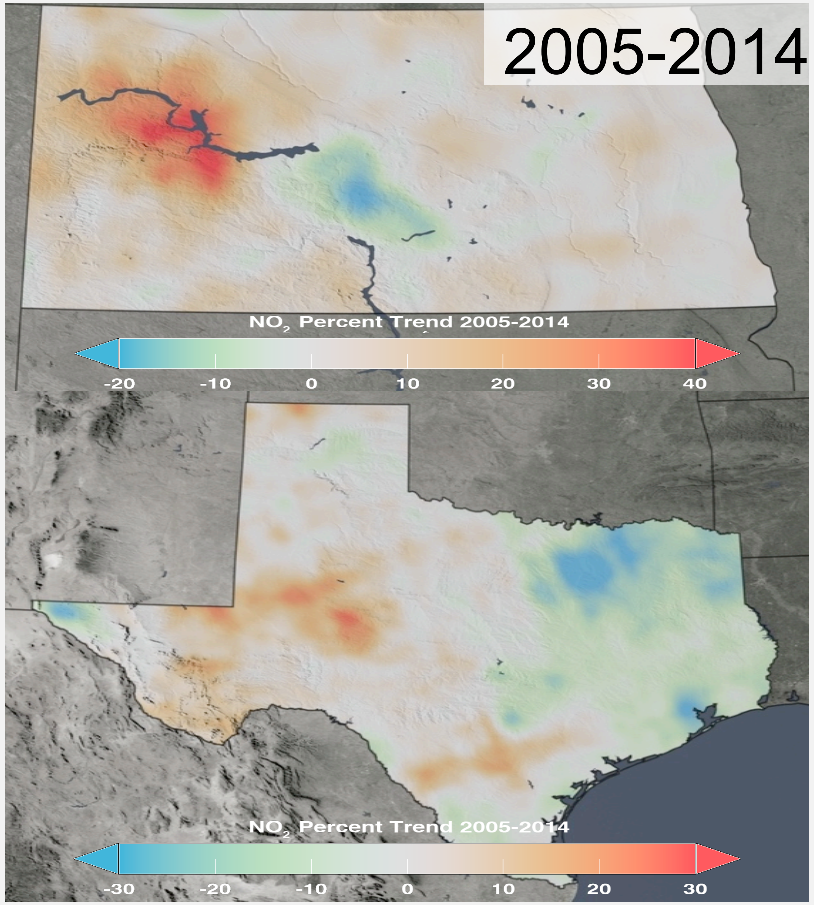


Figure 5 from Streets et al. 2013

Temporal Variations

Satellite observations can be used to monitor changes in emissions over time



North Dakota

Suomi NPP VIIRS Lights at Night

Texas

Courtesy of: Bryan Duncan

Temporal Variations

- Satellite observations can also be used to detect potential short term and unexpected changes in trends, such as reductions in activity due to:
    - economic recession
    - natural disasters (e.g., Hurricane Katrina)
    - policy interventions (e.g., Beijing Olympics)
    - civil unrest

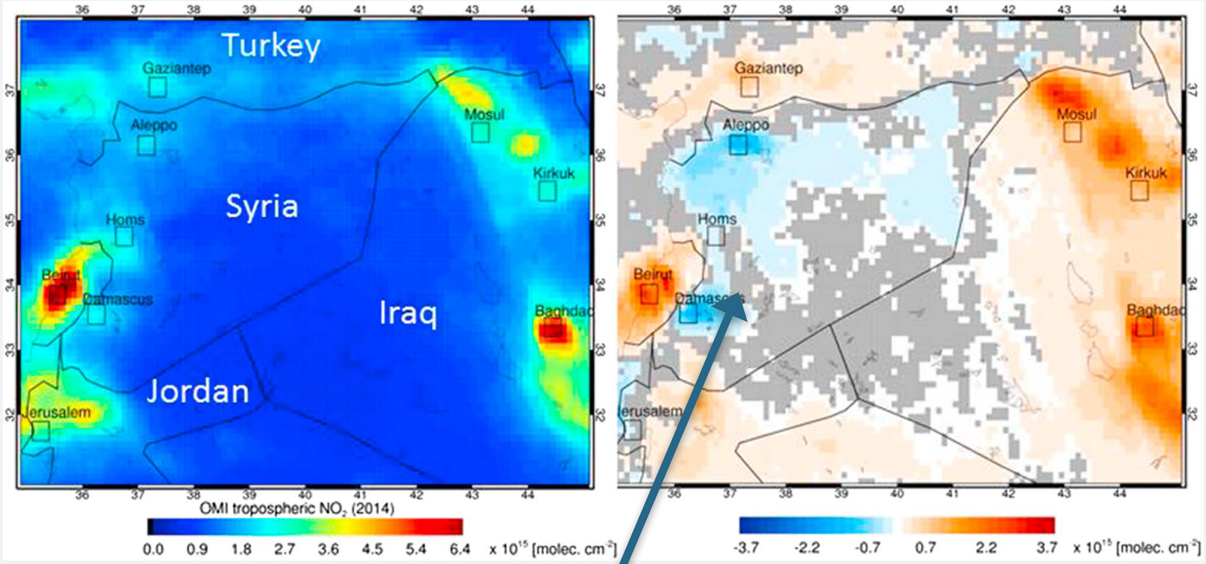
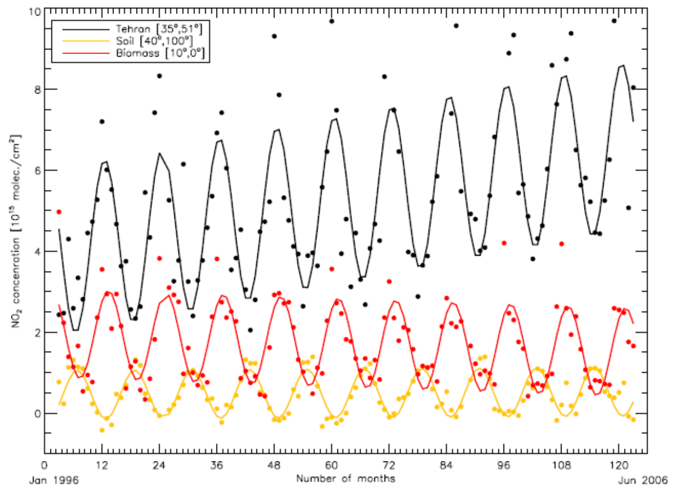


Figure 11 from Duncan et al. 2016

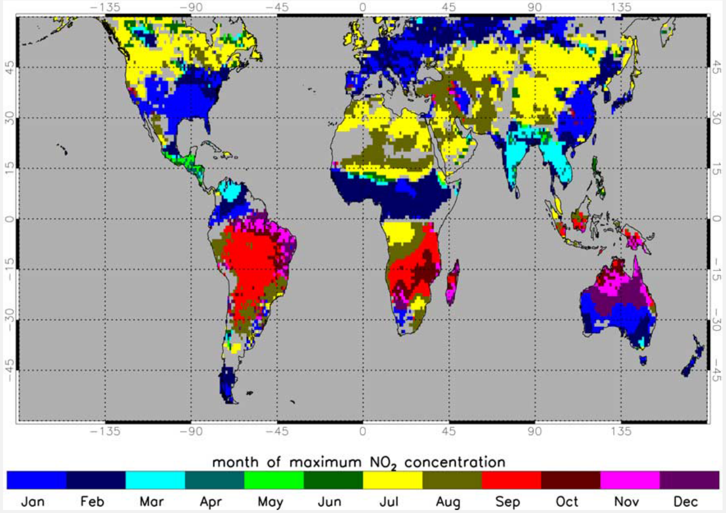
NO_2 Trends from OMI
Damascus: -37.1 ± 10.9%
Aleppo: -40.2 ± 13.6%

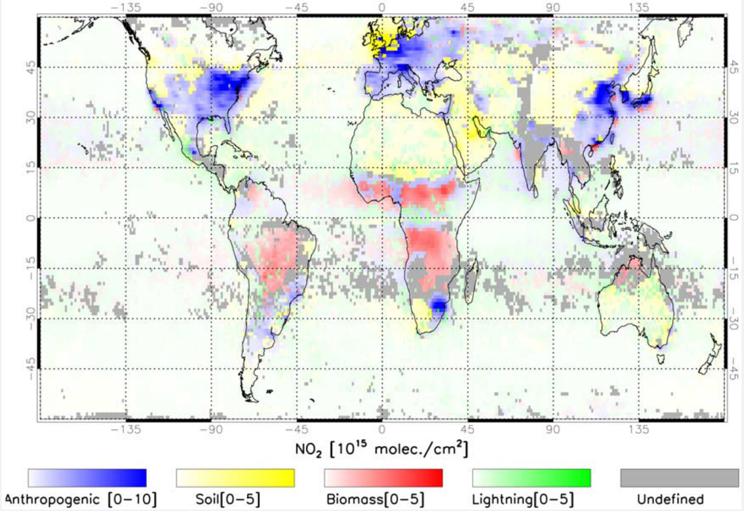
Temporal Variations

- Examine finer temporal emissions cycles
  - Weekly cycles
  - Seasonal cycles of different sources
    - Anthropogenic – Winter
    - Soil – Summer
    - Biomass Burning – Dry Season



Anthropogenic
Soil
Biomass Burning



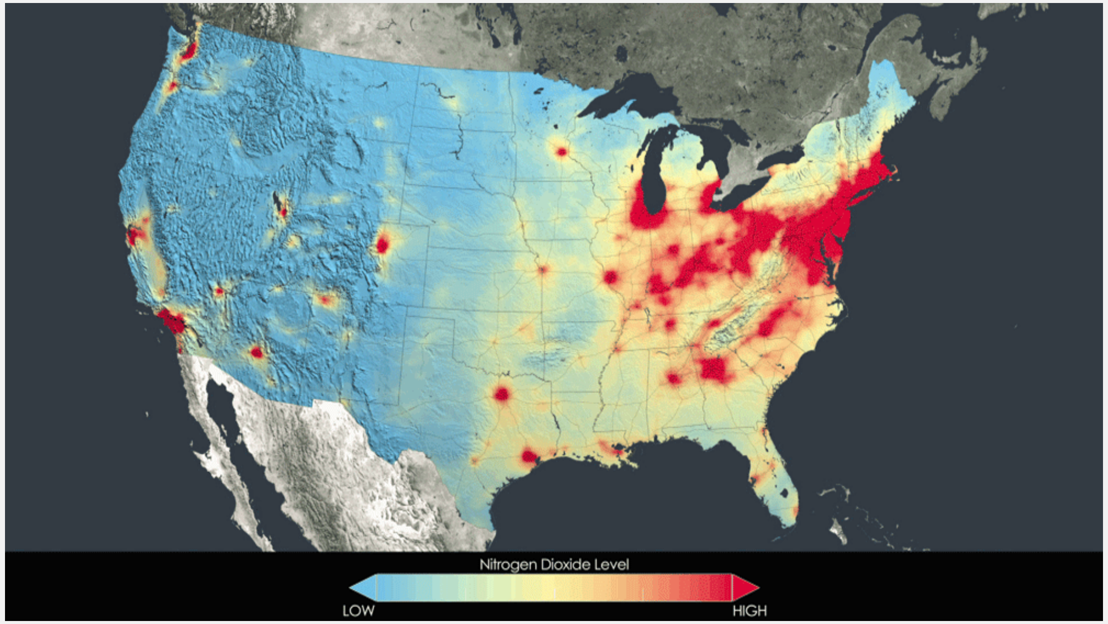


Figures 3, 5, and 7 from van der A. et al. 2008

NO_2 and SO_2

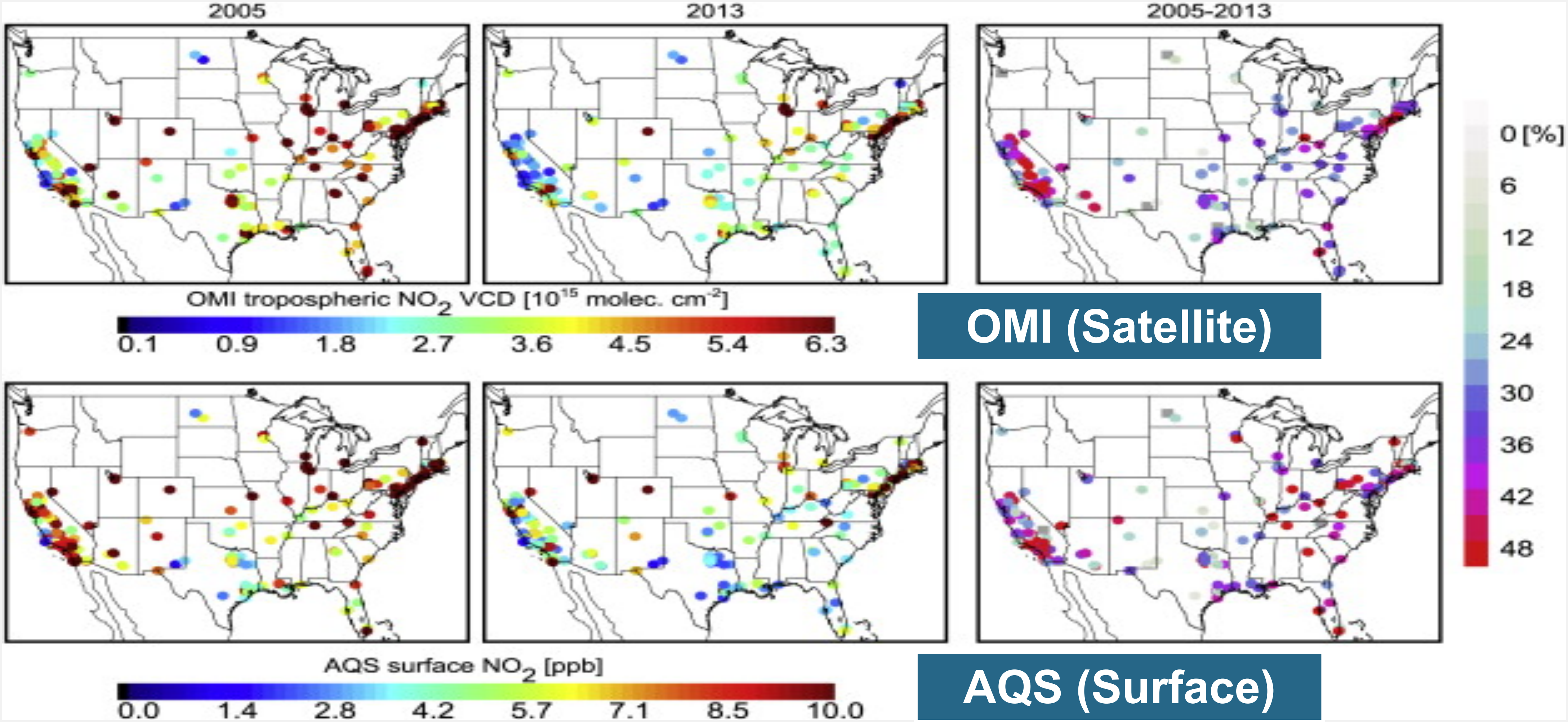
Nitrogen Dioxide (NO_2)

- Why measure NO_2?
  - NO_2 is an ozone precursor and health irritant
  - Sources: Fires, industrial and transportation sources, stationary sources (e.g., power plants), *but* emissions can vary depending on fuel type and conditions
  - Relatively short-lived, so large gradients and high concentrations within the planetary boundary layer (PBL)
  - Satellite observations have been used in many inverse modeling studies



Source: Duncan, B.N. et al. (2016)

OMI Trends in NO_2 Correlate Well With Surface Trends



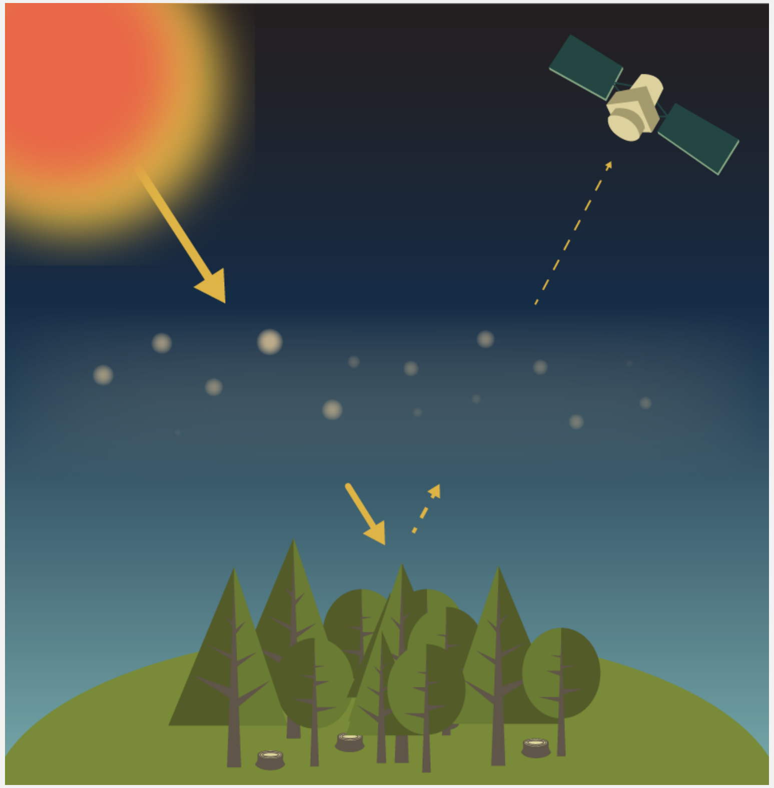
Source: Lamsal, L.N. et al. (2016)

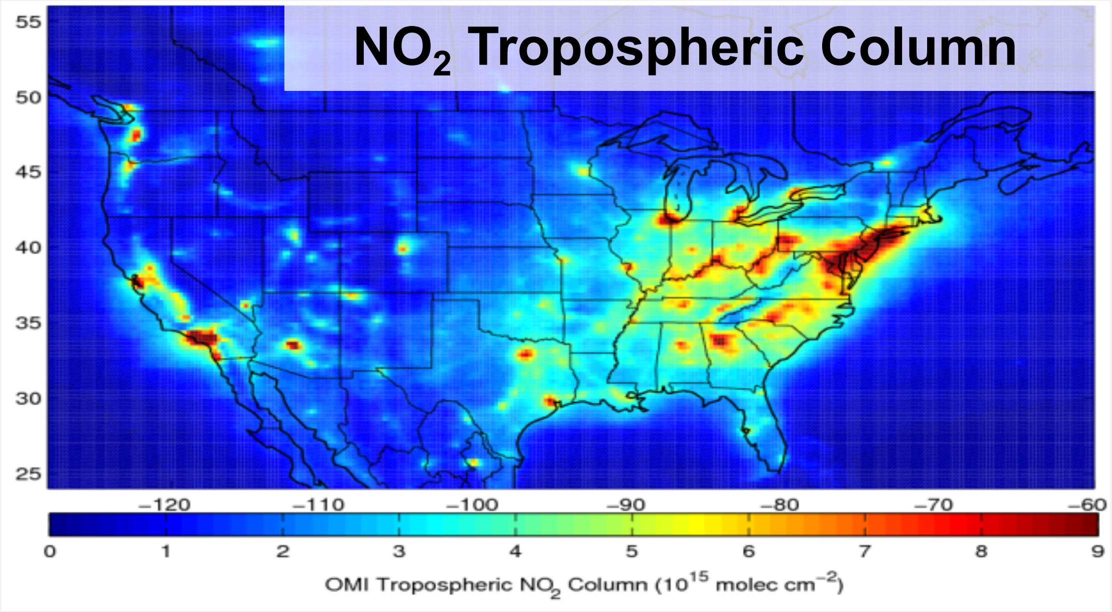
Satellite-Based Surface NO_2

Available from the University of Dalhousie website:
http://fizz.phys.dal.ca/~atmos/martin/?page_id=232

Time Period	1996-2012	2005-2007
Available Product	Annual Mean, 3-Yr Running Mean	Annual Mean (North America and global)
Instruments	GOME, SCIAMACHY, GOME-2	OMI
Overpass Time	~9:30-10:30	~13:30
Product Resolution	$0.1^{\circ} \times 0.1^{\circ}$	$0.1^{\circ} \times 0.1^{\circ}$
Reference	Geddes et al. (2015)	Lamsal et al. (2008, 2010)

Estimating Surface NO_2 From the Tropospheric Column

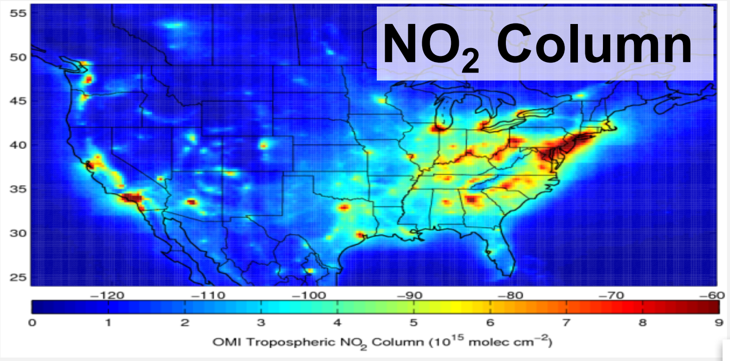




Satellites measure backscattered radiation, from which vertical column densities can be calculated

Courtesy of Randall Martin

Estimating Surface NO_2 From the Tropospheric Column



$$v = \frac{\Omega_{Satellite}}{\Omega_{Model}}$$

$$S = \Omega_{Sat}\ x \left[\frac{vS_{Model}}{v\Omega_{Model} - (v-1)\Omega_{FT\ (Model)}}\right]$$

Use vertical information from an atmospheric chemistry model to estimate the relationship between the column and the surface

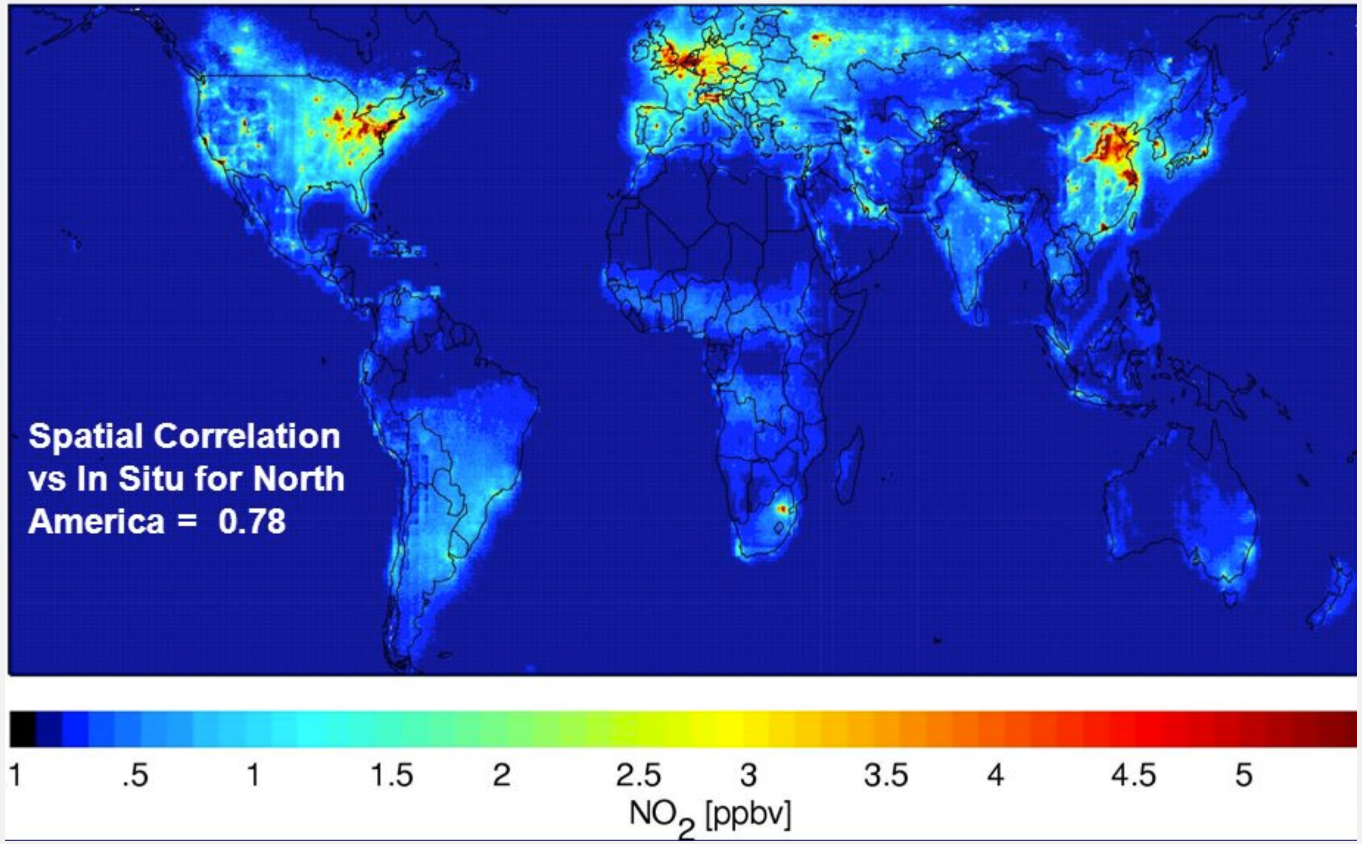
S = Surface Concentration

Ω = Tropospheric Column

FT = Free Troposphere

Courtesy of Randall Martin

Ground-Level Afternoon NO_2 Inferred from OMI for 2005

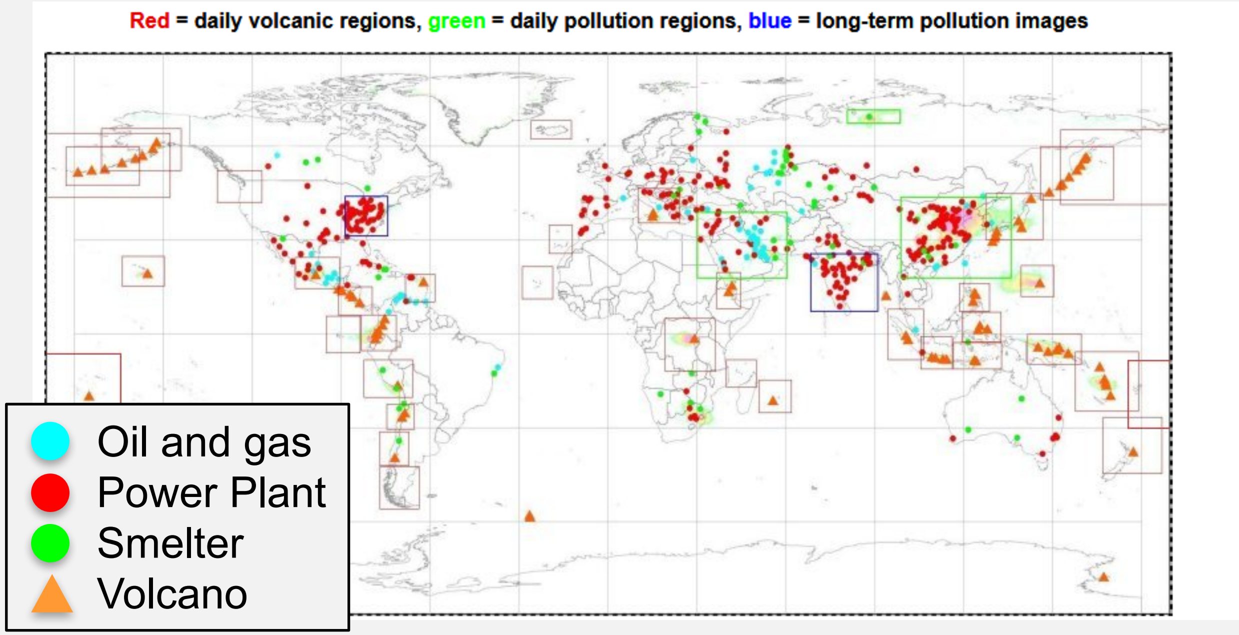


- Note: this is a research product and not an official NASA product

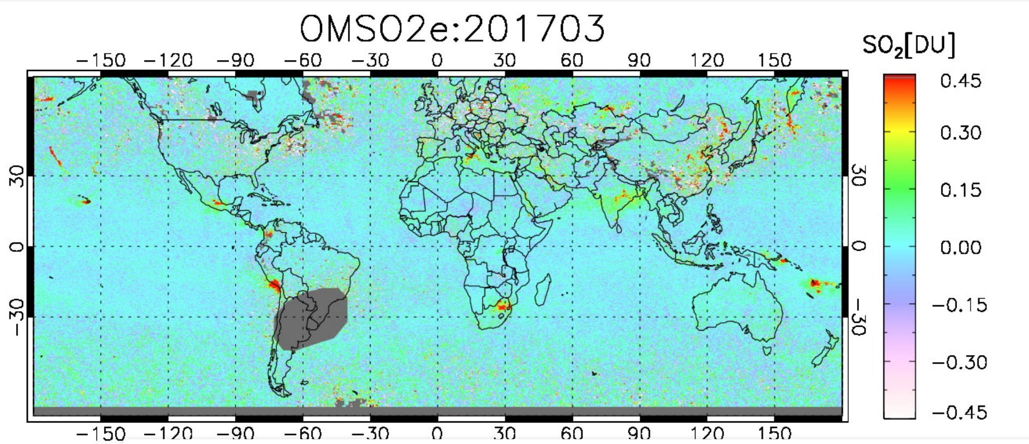
Source: Lok Lamsal

Sulfur Dioxide (SO_2)

- Why measure SO_2?
  - SO_2 has also been linked to adverse respiratory effects
  - Contributes to acid deposition
  - Sources: volcanoes, coal and oil burning



https://so2.gsfc.nasa.gov/



OMI Boundary Layer SO_2 March 2017

https://so2.gsfc.nasa.gov/

OMI SO_2 Gridded Product Summary

SO_2 Product	Level	Data Short Name	Altitude Sensitivity	Use
PBL SO_2	L3 0.25° x0.25°	OMSO2e	0.6 km	Fossil fuel, industry
TRL SO_2	L2G 0.25° x0.25°	OMSO2G	3 km	Optimized for volcanic degassing
TRM SO_2	L2G 0.25° x0.25°	OMSO2G	8 km	Plumes from moderate eruptions
STL SO_2	L2G 0.25° x0.25°	OMSO2G	18 km	Explosive volcanic eruptions

Caveat: Unlike the OMSO2e 'best' product, L2G data is **not** screened for clouds, solar zenith angle, quality flags, and row anomalies

Emissions from OMI SO_2

https://so2.gsfc.nasa.gov/measures.html

Assuming steady state:

Emission $$E = \frac{\alpha}{\tau}$$

Mass of SO_2

Decay time

Emissions from OMI SO2

https://so2.gsfc.nasa.gov/measures.html

Level 2 PBL SO2
Oversampled to 0.04°

Winds from ECMWF

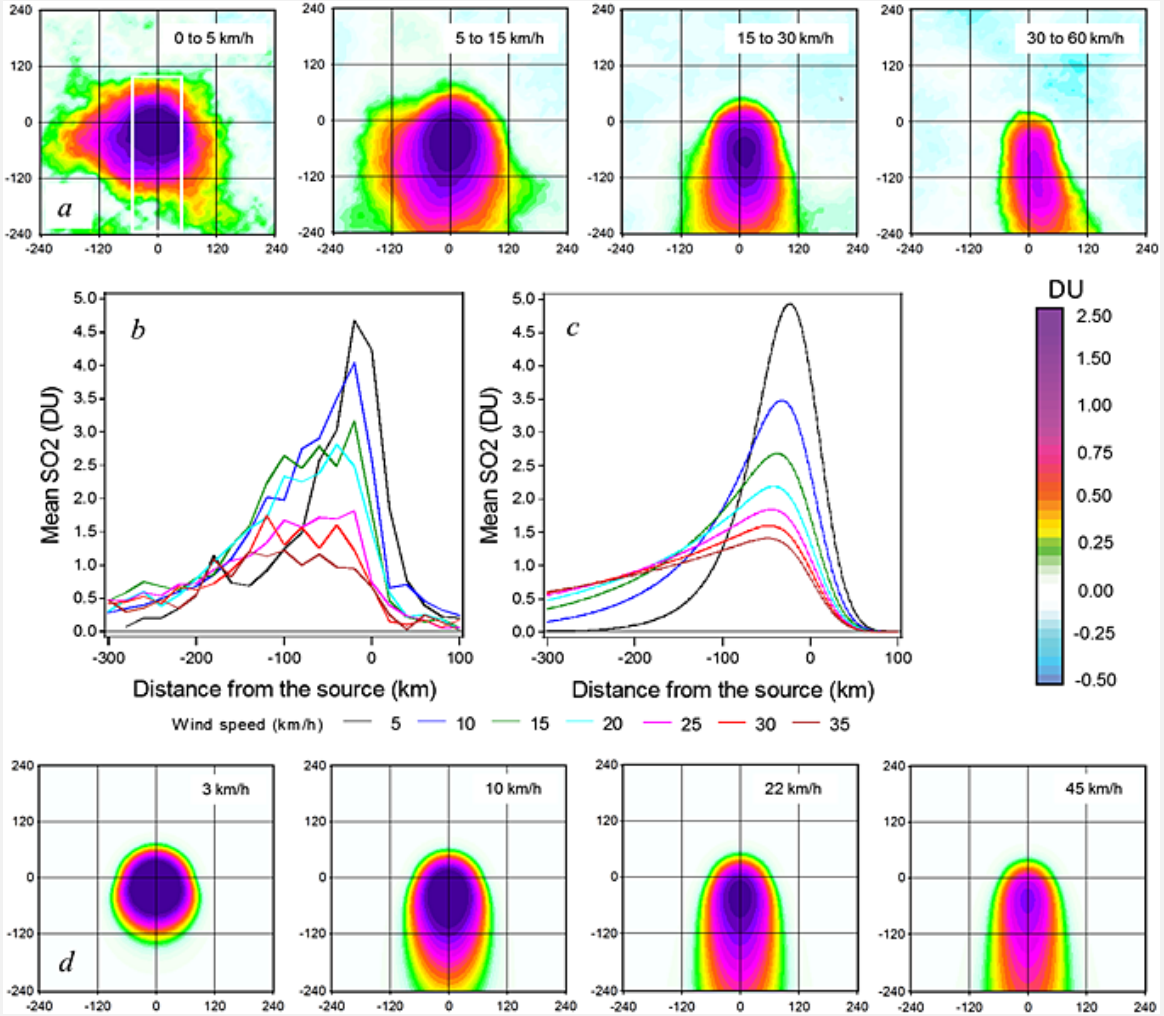
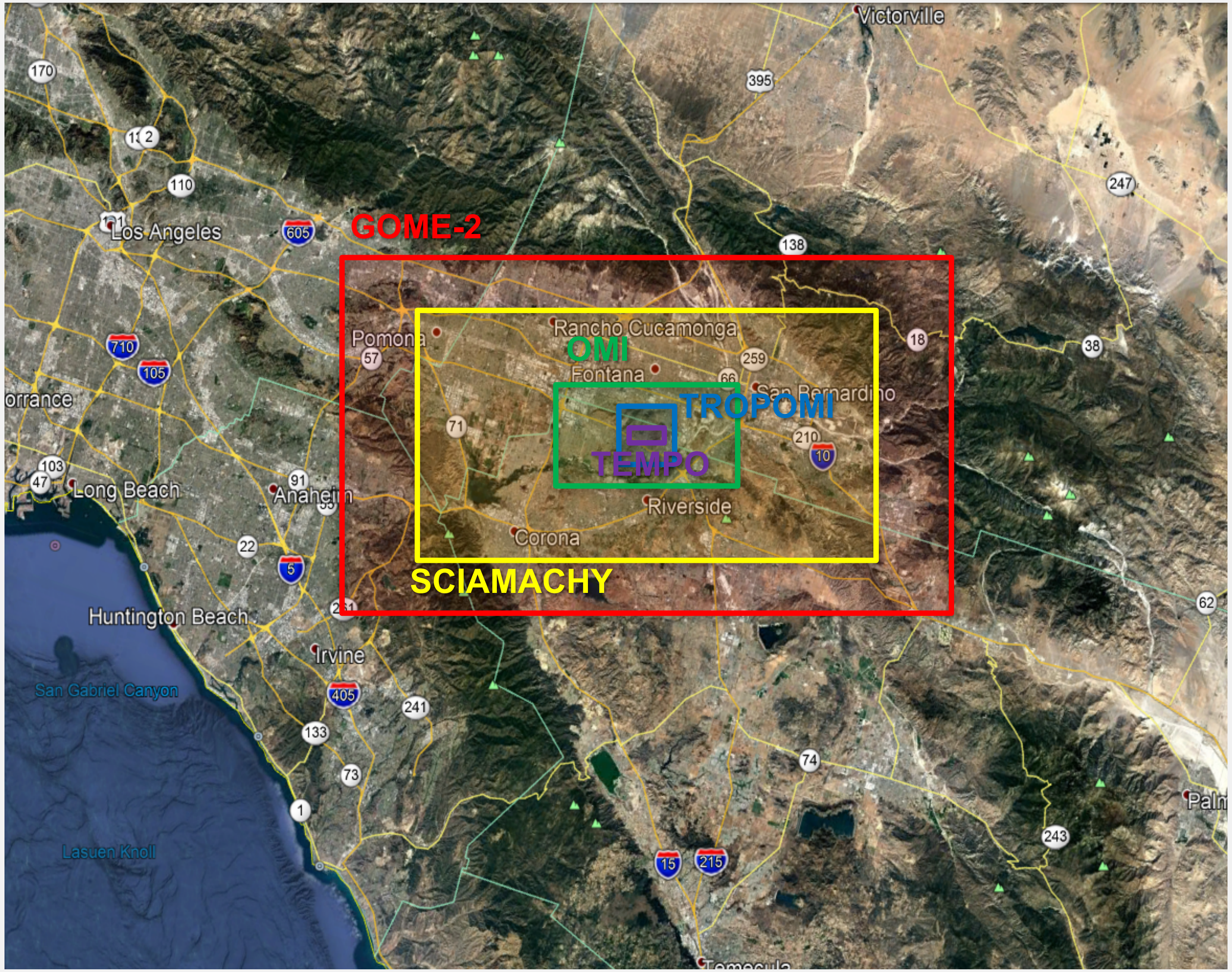


Figure 1, Fioletov et al. 2015

Comparison Chart – NO_2, SO_2

	GOME	SCIAMACHY	GOME-2	OMI	OMPS	TROPOMI
Time Period	1995-2003	2002-2011	2007 - present	2004 - present	2012 - present	2017 launch?
Product/ Pixel Size	320 x 40 km	60 x 30 km	80 x 40 km	13 x 25 km	50 x 50 km	7 x 7 km
Global Coverage	3 days	6 days	1.5 days	Daily	Daily	Daily
Overpass Time	10:30	10:00	09:30	13:45	13:30	N/A
Spectral Region	UV, VIS	UV, VIS	UV, VIS	UV, VIS	UV, VIS	UV, VIS, NIR, & SWIR

Evolution of Spatial Resolution



GOME-2
SCIAMACHY
OMI
TROPOMI
TEMPO

NH_3

Ammonia (NH_3)

- Why measure NH_3?
  - Excess deposition can lead to soil acidification of terrestrial ecosystems and eutrophication of coastal ecosystems
  - Can combine to form ammonium nitrate and ammonium sulfate, which contribute to $PM_{2.5}$
  - Sources: agriculture, animal waste, and industrial emissions
  - Short atmospheric lifetime (hours)
  - Difficult to measure, surface level monitoring of NH_3 is sparse

Measurement Comparison Chart – NH_3

	AIRS	TES	IASI
Time Period	2002 - Present	2004 - Present	2006 - Present
Product / Pixel size	45 x 45 km	5.3 x 8.5 km	12 x 12 km
Global Coverage	Daily	2x/day	Megacities
Overpass Time	13:30	13:45/ 1:45	9:30/21:30
Spectral Region	VIS, IR	Thermal IR	Thermal IR
Detection Limit		1 ppb	2-5 ppb

- Most NH_3 is near the surface, making it challenging to retrieve
- When there is high enough thermal contrast (temperature difference between the surface and the PBL) both retrievals show sensitivity to boundary later NH_3 concentrations
- Heald et al. (2012) using IASI concluded that CA NH_3 emissions were underestimated
- Zhu et al. 2013 – using TES, along with GEOSChem and its adjoint, concluded that the NH_3 emission inventory was broadly underestimated in the West US

Contact Information

- To obtain NH_3 data, contact:
- AIRS
  - Juying Warner: jwarner5@umd.edu
- IASI
  - Pierre Coheur: pfcoheur@ulb.ac.be
- TES
  - Karen Cady-Pereira: kcadyper@aer.com

AIRS NH3 @ 918 hPa 2002-2016

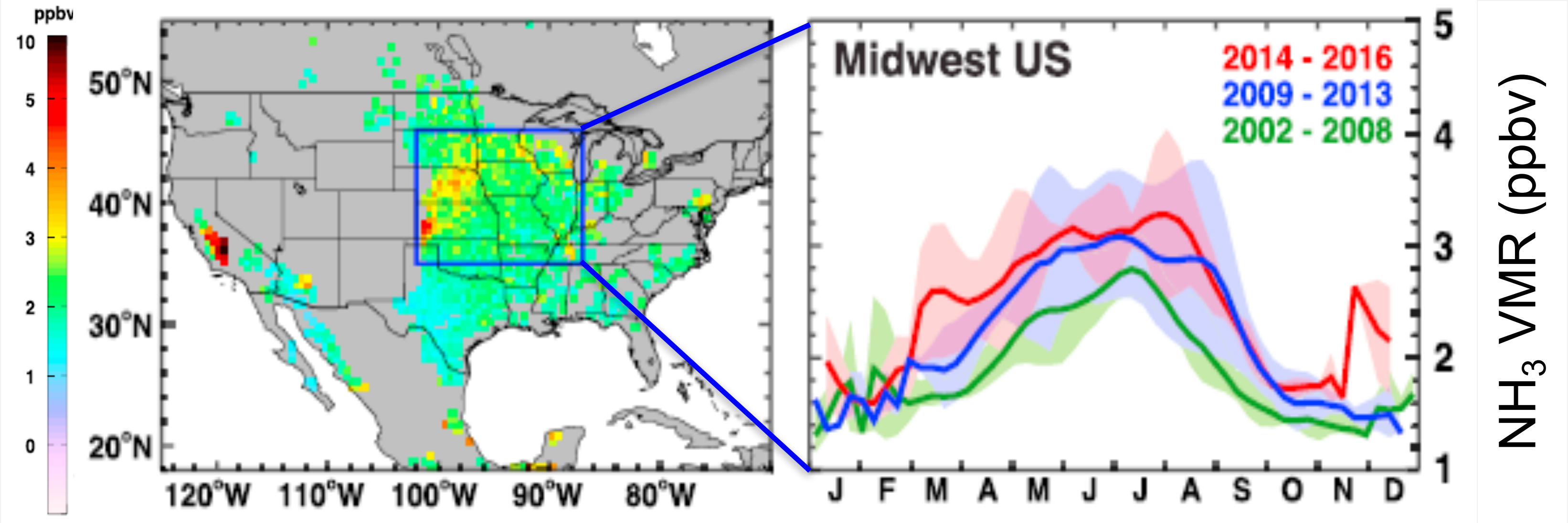
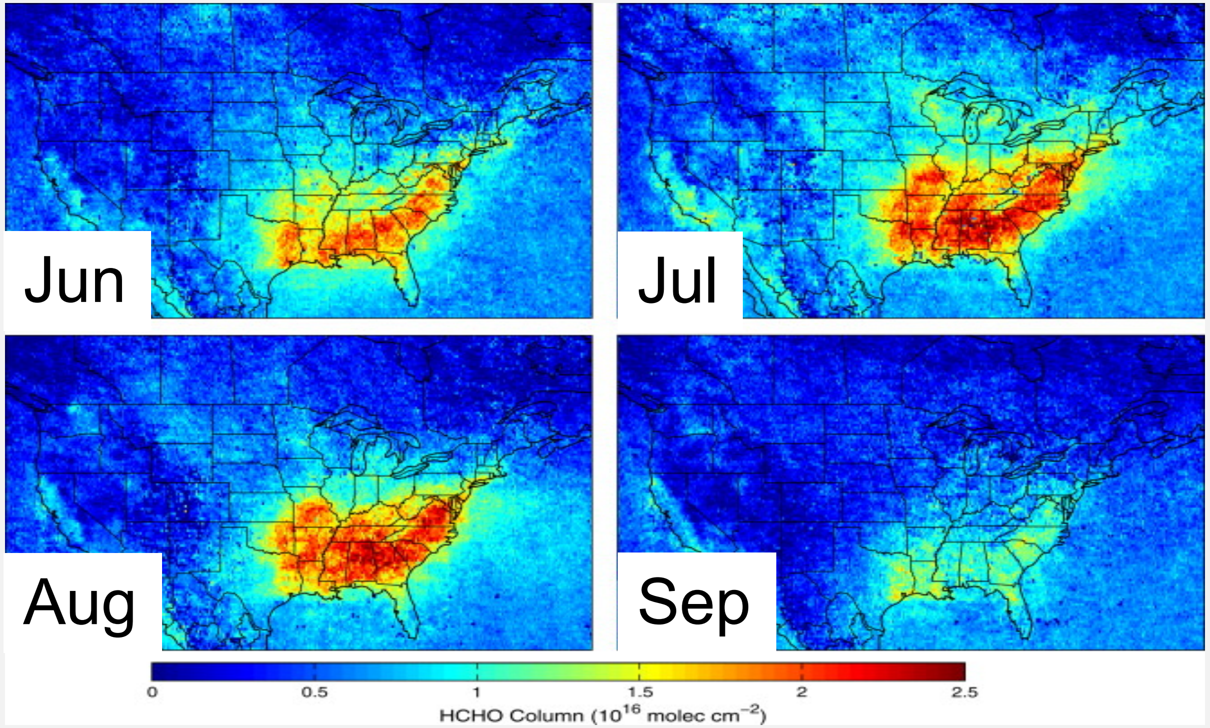


Figure 2 from Warner et al. 2017

HCHO

Formaldehyde (CH_2O)

- Why measure formaldehyde?
  - Formaldehyde is an ozone precursor and can serve as a proxy for total VOC chemical reactivity and isoprene emissions
- VOC sources: Biogenic, anthropogenic, and fires
- Short lifetime (few hours)



Source: Martin, Randall. Satellite remote sensing of surface air quality. Atmospheric Environment 42(34), 7823-7843, 2008.

HCHO

- Lei Xhu et al. 2017
  - Calculated annual mean surface concentration of HCHO using OMI and associated cancer risk

First, oversampled to 5 x 5 km^2 to relate concentrations to population estimates

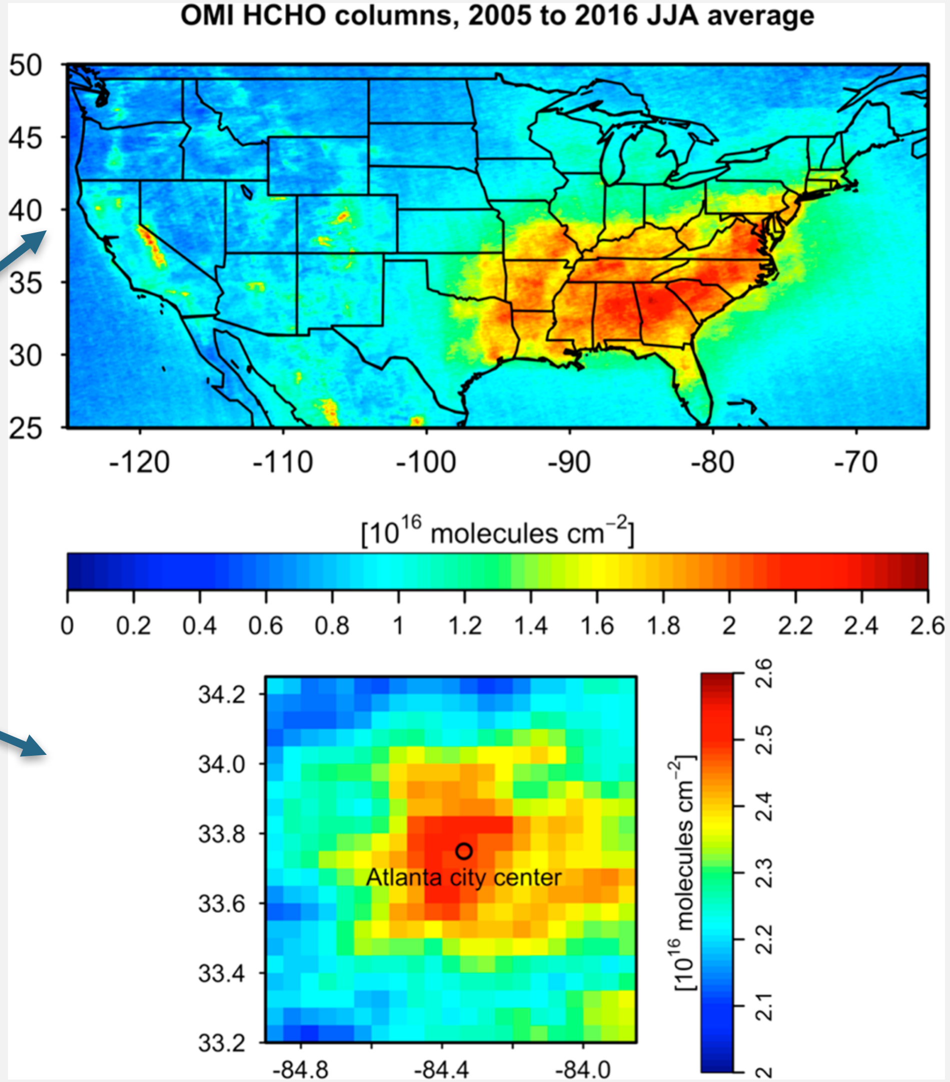


Figure 2 from Xhu et al. 2017

HCHO

For each grid cell:

$$\bar{C} = \bar{\Omega}\,\gamma_1\,\gamma_2\,\gamma_3$$

$\bar{C}$ = annual mean surface concentration

$\bar{\Omega}$ = Oversampled summer mean column

γ_1 = ratio of midday surface to column concentrations in summer

γ_2 = ratio of 24 h average to midday concentrations in summer

γ_3 = ratio of annual mean to summer mean concentrations

OMI-Derived Mean HCHO and Associated Cancer Risk

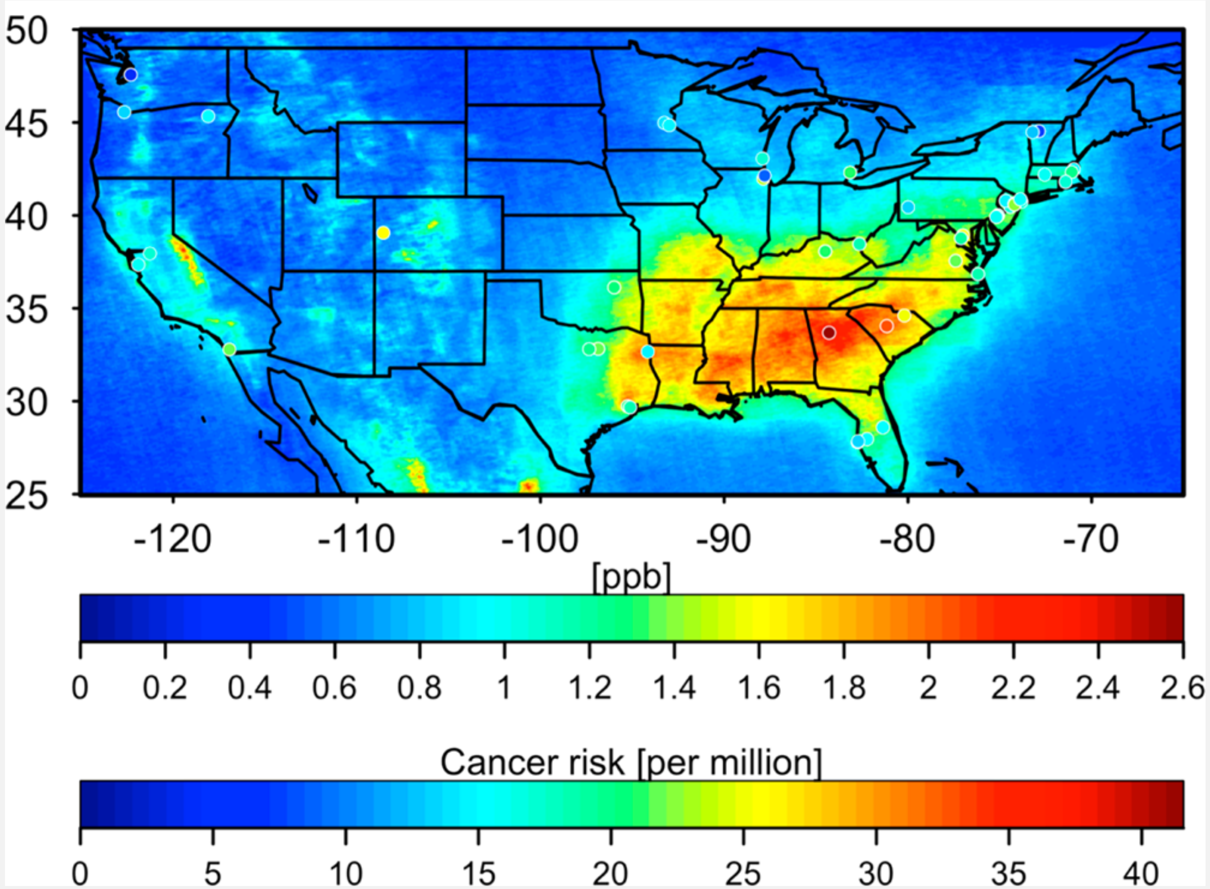


Figure 7 from Xhu et al. 2017

Measurement Comparison Table – HCHO

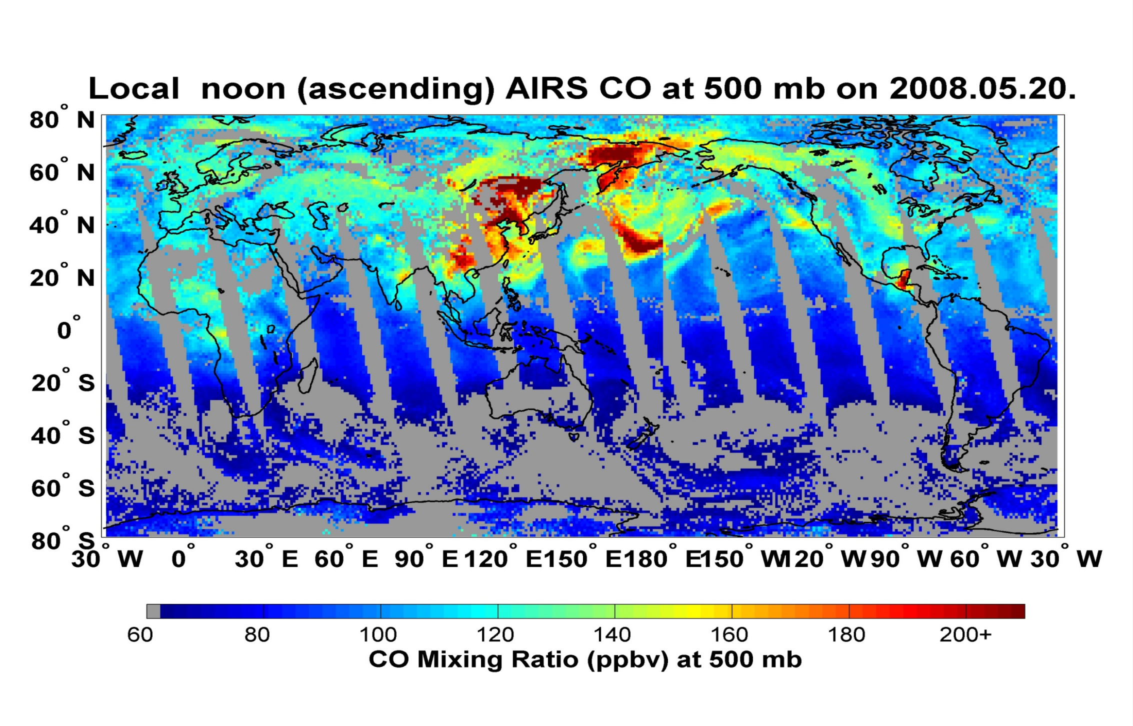
	GOME	SCIAMACHY	GOME-2	OMPS	OMI
Time Period	1995 – 2003	2002 – 2011	2007 – present	2012 - present	2004 – present
Product / Pixel Size	320 x 40 km	60 x 30 km	80 x 40 km	50 x 50 km	13 x 25 km
Global Coverage	3 days	6 days	1.5 days	Daily	Daily
Overpass Time	10:30	10:00	9:30	13:30	13:45
Spectral Region	UV, VIS	UV, VIS	UV, VIS	UV, VIS	UV, VIS

- Caution should be used when using these data for quantitative analyses
  - When compared to observations, satellite observations of HCHO are biased low

Carbon Monoxide (CO)

Carbon Monoxide

- Why measure CO?
  - Major global precursor for O_3, and dominant sink for OH
  - Relatively long lifetime (~1-2 months) makes it a useful tracer of transport
- Sources: Chemical production (oxidation of VOCs) and incomplete combustion (fossil fuel burning, fires)
- Instruments (e.g., MOPITT, AIRS) tend to have good sensitivity to CO in the mid-troposphere (~500 mb)
- Current sensors: AIRS, MOPITT, IASI



Measurement Comparison Table - CO

	MOPITT	AIRS	IASI
Product / Pixel Size	22 x 22 km	14 x 14 km	12 x 12 km
Swath Width	650 km	1,650 km	2,200 km
Global Coverage	3 days	2x per day	2x per day
Overpass Time	10:30	13:30	9:30, 21:30
Product Resolution	L3: 1° Grid	L3: 1° Grid	NO L3 Product
Products Available	L2 L3, Daily, Monthly	L2 granule L3	L2 NOAA & ESA
Vertical Sensitivity	mid & lower troposphere	mid troposphere	mid troposphere
Product Accuracy	TIR: 2% Near Surface: 3%	10-20%	<10%

TIR vs. NIR vs. TIR-NIR: MOPITT

- Thermal IR (TIR)
  - 4.6 µm
  - Most sensitive to mid-tropospheric CO
  - Highest temporal stability
- Near IR (NIR)
  - 2.3 µm
  - Sensitivity at all altitudes
  - Daytime only
  - Most appropriate for analysis of total columns
- TIR-NIR
  - Greatest vertical resolution
  - Largest sensitivity to lower tropospheric CO
  - However, random retrieval errors and bias drift
  - Use only daytime, over land

Deeter et al. 2017, https://www.atmos-meas-tech.net/10/2533/2017/amt-10-2533-2017.pdf

Questions & Discussion Prompts

- Name one way satellite observations can supplement an emissions inventory.

- What are the advantages and limitations of using satellite data to estimate surface concentrations?


Questions